LLNL-JRNL-637412

Changes in Concurrent Precipitation and Temperature Extremes

Z. Hao, A. AghaKouchak, T. J. Phillips

May 24, 2013

Environmental Research Letters

Changes in Concurrent Precipitation and Temperature Extremes

Zengchao Hao
University of California Irvine, E4130 Engineering Gateway Irvine, CA 92697, USA.

Amir AghaKouchak
University of California Irvine, E4130 Engineering Gateway Irvine, CA 92697, USA.
E-mail: amir.a@uci.edu

Thomas J. Phillips
Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.

Abstract. While numerous studies have addressed changes in climate extremes, analyses of concurrence of climate extremes are scarce, and climate change effects on joint extremes are rarely considered. This study assesses the occurrence of joint (concurrent) continental precipitation and temperature extremes in Climate Research Unit (CRU) and University of Delaware (UD) observations, and in 13 Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate simulations. Analysis of concurrent climate extremes reveals information that is not otherwise apparent, and hence this study provides a stringent assessment of how well model simulations of historical climate replicate the observed climate statistics. The joint occurrences of precipitation and temperature extremes simulated by CMIP5 climate models are compared against those derived from the CRU and UD observations for Warm/Wet, Warm/Dry, Cold/Wet, and Cold/Dry combinations of joint extremes. The number of occurrences of these four combinations during the second half of the 20th century (1951-2004) is assessed on a common global grid. CRU and UD observations show substantial increases in the occurrence of joint Warm/Dry and Warm/Wet combinations for the period 1978-2004 relative to 1951-1977. The results show that with respect to the sign of change in the concurrent extremes, the CMIP5 climate model simulations are in reasonable agreement overall with observations. However, the results reveal notable discrepancies between regional patterns and the magnitude of change in individual climate model simulations relative to the observations of precipitation and temperature.

1. Introduction

The interaction and dependence between precipitation and temperature, mainly due to the thermodynamic relations between the two variables, have been recognized in numerous studies. Precipitation and temperature data are generally interdependent, and their co-variability has been explored at different spatial and temporal scales ((Zhao & Khalil 1993); (Trenberth & Shea 2005); (Adler, Gu, Wang, Huffman, Curtis & Bolvin 2008); (Liu, Allan & Huffman 2012)). Various parametric and non-parametric joint distribution functions also have been used to represent this interdependence ((Tebaldi & Sansó 2008); (Sexton, Murphy, Collins & Webb 2012); (Watterson 2011); (Estrella & Menzel 2012)).

While extreme values of precipitation and temperature often are addressed independently by employing univariate statistical methods ((Cooley, Nychka & Naveau 2007); (Katz 2010); (Zhang, Alexander, Hegerl, Jones, Tank, Peterson, Trewin & Zwiers 2011); (AghaKouchak, Ciach & Habib 2010)), analyses of concurrence of climate extremes are scarce, and climate change effects on joint extremes are rarely investigated. Simultaneous occurrences of such precipitation and temperature exceedances are often described in terms of Warm/Wet, Warm/Dry, Cold/Wet, and Cold/Dry climate combinations ((Zhang, Vincent, Hogg & Niitsoo 2000); (Beniston 2009); (Estrella & Menzel 2012)). (Zhang et al. 2000), for example, analyzed the trends of precipitation and temperature, as well as the areas affected by the joint abnormal conditions in Canada, based on the four combinations of Wet/Dry and Warm/Cold climate extremes. (Beniston 2009) also investigated trends in the joint quantiles of precipitation and temperature across Europe using the same four climatic combinations.

Because the joint representation of climate extremes may reveal information that is not otherwise apparent, this approach can provide a stringent assessment of how well model simulations of historical climate replicate the observed climate statistics. The objective of the present study is to assess changes in concurrent precipitation and temperature extremes based on observations, and the ability of multiple Coupled Model Intercomparison Project Phase 5 (CMIP5; (Taylor, Stouffer & Meehl 2012)) simulations to reproduce the joint statistics of the observed extreme values for the climate of the 20th century.

2. Data and Method

In this study, ground-based observations and 13 CMIP5 historical simulations (1951-2004) of precipitation and temperature are used to investigate concurrent extremes. Monthly 0.5×0.5^o gridded observationally based continental precipitation and temperature data for the same period provided by the Climate Research Unit (CRU; Version 3.1) are used as validation references ((New, Hulme & Jones 2000); (Mitchell & Jones 2005)). Since observations are also subject to uncertainties ((Thorne, Parker, Christy & Mears 2005); (Morice, Kennedy, Rayner & Jones 2012)), the gridded monthly terrestrial air temperature and precipitation data sets for the period 1951-2004 from the University of Delaware (UD) are used as an alternative source of ground-based observation ((Nickl, Willmott, Matsuura & Robeson 2010)). The UD data include a large number of stations from both the Global Historical Climate Network (GHCN) and the archive of Legates and Willmott monthly and annual station records ((Legates & Willmott 1990*a*); (Legates & Willmott 1990*b*)). These data are interpolated to a 0.5 degree by 0.5 degree resolution and have been used in a variety of studies ((Rawlins, Bradley & Diaz 2012); (Sheffield, Wood & Roderick 2012)). It is acknowledged, however, that the ground-based observations are subject to their own biases and uncertainties, especially over more remote African, Asian, and South American regions where measurements are comparatively sparse, as well as in the first half of the 20th century generally ((New, Hulme & Jones 1999); (New et al. 2000); (Tanarhte, Hadjinicolaou & Lelieveld 2012)). This study therefore is limited to the second half of the 20th century for which more reliable ground-based observations are available. For consistent comparison, the ground-based observations and the mostly coarser-resolution CMIP5 climate simulations are all remapped onto a common 2×2^o global grid.

The 25% and 75% quantiles of precipitation and temperature are used as threshold levels for defining the joint extremes. Following (Beniston 2009), the combination of the precipitation and temperature quantiles T75/P75, T75/P25, T25/P75 and T25/P25 represent the four climate combinations: Warm/Wet, Warm/Dry, Cold/Wet, and Cold/Dry, respectively. In other words, concurrent extremes are defined as being simultaneously in an outer quartile of both temperature and precipitation. Here, P75 (T75) indicates precipitation (temperature) occurrences above the 75% quantile, while P25 and (T25) denotes occurrences below the 25% quantile. For purposes of this study, the term "extreme" thus denotes a rather modest departure from the mean, i.e. above the 75% percentile or below the 25% percentile. However, the joint precipitation-temperature statistics are found to be relatively insensitive to the choice of quantile levels, since similar patterns of changes to concurrent extremes are obtained when alternatively 90/10% thresholds are used - not presented here for brevity. The joint occurrences of extremes during the late 20th century (1978-2004) are compared with the period (1951-1977) at each 2×2^o grid point, where the joint occurrences in each period are obtained by counting the frequency of occurrences of T75/P75, T75/P25, T25/P75, and T25/P25 combination. The percent change in the joint occurrence of extremes (as well as the absolute number of occurrences) during 1978-2004 relative to 1951-1977 are then obtained for the ground-based observations and each CMIP5 climate simulation. Here the percent change is defined as 100 $\times$ the difference between the number of occurrences in the two periods divided by the number of occurrences in the first (base) period.

3. Results

The percent changes in occurrence of concurrent extremes (Warm/Wet, Warm/Dry, Cold/Wet, Cold/Dry) based on ground-based observations and CMIP5 historical simulations are presented in Figures 1 to 4. The changes in the absolute number of concurrent extremes are also provided as supplement material (Figures S1 to S4).

The percent changes in the Warm/Wet combinations for ground-based observations (CRU and UD data) and for each selected CMIP5 historical simulations between the two periods are shown in Figure 1. The CRU and UD data sets indicate that the joint occurrence of Warm/Wet combinations has significantly increased in the 1978-2004 period relative to that of 1951-1977. This result is consistent with previous findings that extremely hot days and heavy precipitation events have become more common since 1950 ((Field, Barros, Stocker, Qin, Dokken, Ebi, Mastrandrea, Mach, Plattner, Allen et al. 2012); (Easterling, Meehl, Parmesan, Changnon, Karl & Mearns 2000); (Smith, Arkin, Ren & Shen 2012)). Also, numerous studies have shown that the global surface temperature (both mean and extreme values) and precipitation extremes have increased in the second half of the 20th century (e.g., ((Nicholls, Gruza, Jouzel, Karl, Ogallo, Parker et al. 1996); (Easterling et al. 2000); (Vose, Wuertz, Peterson & Jones 2005); (Alexander, Zhang, Peterson, Caesar, Gleason, Klein Tank, Haylock, Collins, Trewin, Rahimzadeh, Tagipour, Ambenje, Rupa Kumar, Revadekar & Griffiths 2006); (Hansen, Ruedy, Sato & Lo 2010); (Lawrimore, Menne, Gleason, Williams, Wuertz, Vose & Rennie 2011); (Jones, Lister, Osborn, Harpham, Salmon & Morice 2012)).

The joint analysis of these extremes from the CRU and UD data highlights that, at high latitudes (e.g., Canada and Siberia), as well as in tropical regions (central Africa and Amazon), the occurrences of Warm/Wet extremes has increased substantially in 1978-2004 relative to 1950-1977, while a few areas, such as parts of southern China, South America, and eastern United States, exhibit a decrease in these occurrences. It is worth noting that, in a recent study (Field et al. 2012) argue that regional and global assessment of extreme temperature data is consistent with the warming at the global scale reported in (IPCC 2007). However, few regions exhibit opposite behavior (showing cooling patterns) including parts of the eastern United States, central North America, and South America (see (Field et al. 2012)), consistent with our observations of concurrent extremes.

Generally, most of the CMIP5 climate simulations are in qualitative agreement with CRU and UD observations and show an increase in the occurrence of Warm/Wet combinations across the globe, although the magnitude of the increase differs by individual model at a regional scale. For example, the patterns of change in Warm/Wet extremes simulated by the CSIRO-Mk3.6.0 and MIROC5 models differ substantially from those of the CRU and UD observations. Figure 1 also demonstrates that most, but not all, models agree with CRU and UD observations that the Warm/Wet combinations have increased over several parts of the world, including the western United States, Africa, Australia and the Middle East. On the other hand, the CMIP5 models exhibit regional discrepancies in representing the observed Warm/Wet extremes, particularly over southern India, parts of China and the Amazon region.

Figure 2 displays the percent change in occurrence of the Warm/Dry extremes (high temperature and low precipitation) in 1978-2004 relative to 1951-1977. The simulation of Warm/Dry extremes is of particular concern because of their association with occurrences of heat waves and droughts that can cause tremendous environmental and societal damage ((Sivakumar 2006); (Lyon 2009); (Albright, Pidgeon, Rittenhouse, Clayton, Wardlow, Flather, Culbert & Radeloff 2010)). As shown from the CRU and UD observations, the joint occurrence of Warm/Dry extremes has increased in recent years in many areas across the globe, including Africa, eastern Australia, northern China, parts of Russia and the Middle East. Most CMIP5 climate simulations roughly agree with the locations of observed Warm/Dry extremes, especially over Africa, Amazonia and the Middle East; however, notable discrepancies also exist between individual climate simulations and the CRU and UD observations. For example, while the observations and several CMIP5 simulations (e.g., BCC-CSM1.1, CanESM2, and CCSM4 models) indicate an increase in Warm/Dry combinations across Africa, other simulations (e.g., by the MIROC 5) imply a slight decrease in occurrences of Warm/Dry combinations in large areas of Africa.

The percent change in the Cold/Wet combinations is shown for the CRU and UD observations and for each CMIP5 simulation in Figure 3, where it is seen that most of the simulations are consistent with the observed patterns of change in Cold/Wet extremes. Overall, ground-based observations and CMIP5 model simulations indicate that the concurrence of the Cold/Wet combinations has decreased over most parts of the globe, except over the eastern United States and parts of China where the Cold/Wet combinations have increased. However, regional simulation discrepancies also are evident. For instance, the ground-based observations exhibit a decrease in the Cold/Wet combinations in eastern Australia that is replicated by most model simulations, while the CCSM4 and GFDL-CM3 show an increase in the Cold/Wet combinations. The ground-based observations show an increase in the Cold/Wet combinations in the eastern to northeastern United States. Except GISS-E2-H and CESM1-BGC, however, CMIP5 model simulations display changes opposite to those implied by the CRU and UD observations over many regions across land.

Similar to the Cold/Wet cases, both observations and CMIP5 simulations indicate a decrease in the concurrence of Cold/Dry conditions over most parts of the globe. However, there are substantial and widespread differences between CMIP5 simulations of Cold/Dry extremes and those of the CRU and UD data (Figure 4), with the BCC-CSM1.1, CanESM2, CCSM4 simulations showing better overall agreement with the CRU and UD observations. One can see that there are inter-model variations in the sign of change (decrease/increase in Cold/Dry conditions) over certain regions including Australia, Eurasia and eastern China. It is worth mentioning that both Figures 3 and 4 indicate that even over high latitudes and cold regions, the occurrence of joint Cold/Dry combinations has decreased in 1978-2004 relative to 1951-1977.

Figure 5 summarizes the probability of detection (POD) of the sign of change in the CMIP5 climate-model simulations for the four combinations of Warm/Wet, Warm/Dry, Cold/Wet, and Cold/Dry extremes with respect to CRU observations. Here, the POD is defined as the fraction of grids in which the sign of change in the number of joint occurrences (increase, decrease, neutral) in CMIP5 model simulations agrees with the ground-based observations. The POD values of the CMIP5 climate models for the four combinations of the extremes range between about 0.60 - 0.85, indicating 60% to 85% agreement in the sign of change. However, the magnitudes of changes in the extremes and their detailed patterns may be substantially different from one model to another. Not shown here for brevity is the POD values of CMIP5 models against the UD data. Overall, models exhibit similar qualitative performance with respect to both CRU and UD data sets (i.e., a relatively poorly performing model with a low POD score relative to CRU also scores low relative to UD).

It is worth noting that the climate model simulations are not forced with actual historical sea surface temperature observations. For this reason, the climate models cannot necessarily reproduce the observed sequences of El Niño Southern Oscillation, Pacific Decadal Oscillation, and the Atlantic Multidecadal Oscillation events. This indicates that these climate models cannot be expected to have the observed geographical distribution of extremes in a given year, as climatic extremes are affected by these observed natural phenomena ((Peterson, Stott & Herring 2012); (Kenyon & Hegerl 2010)). One can argue that the Atmospheric Model Intercomparison Project (AMIP) models with prescribed sea surface temperatures would produce the patterns of extremes on land more reliably.

4. Conclusions

The observed increase in heat waves, droughts and floods which have severely impacted the environment and society over the past several decades, has brought much-needed attention to the analysis of climate extremes ((AghaKouchak, Easterling, Hsu, Schubert & Sorooshian 2012); (Hegerl, Hanlon & Beierkuhnlein 2011); (Field et al. 2012)). Numerous studies have addressed changes in climate extremes. However, the concurrence of observed climatic extremes and their simulation by climate models has received considerably less scientific attention.

The concurrences of precipitation and temperature extremes are assessed using ground-based CRU and UD observations and the CMIP5 climate model simulations for the following four combinations of joint extremes: Warm/Wet (high temperature and high precipitation), Warm/Dry (high temperature and low precipitation), Cold/Wet (low temperature and high precipitation), and Cold/Dry (low temperature and low precipitation). The percent change in the joint occurrence of extremes (and in the absolute number of occurrences) during 1978-2004 is compared with the baseline (1951-1977) extreme occurrences at each global grid point. Based on the CRU and UD observations, the occurrences of joint Warm/Dry and Warm/Wet extremes have increased substantially across the globe. The Warm/Wet extremes have particularly increased over high latitudes and in tropical regions, whereas the Warm/Dry extremes also have increased in many other areas, including Africa, eastern Australia, northern China, parts of Russia and the Middle East. On the other hand, the Cold/Wet and Cold/Dry extremes combinations have decreased over most parts of the globe.

The agreement between the CMIP5 climate model simulations of concurrent extremes with the ground-based observations is assessed using the probability of detection (POD) of the sign of change, defined as the fraction of grids in which the sign of change in the number of joint occurrences of extremes (increase, decrease, neutral) in CMIP5 model simulations agrees with the ground-based observations. The results show that with respect to the sign of change in the concurrent extremes, the CMIP5 climate model simulations are in reasonable agreement with observations. However, there are notable discrepancies in regional patterns as well as biases in the magnitudes of change in individual climate model simulations relative to the observations of precipitation and temperature extremes. Further details of the statistical characteristics of the CMIP5 simulations that may account for these issues are currently under investigation.

Acknowledgments

The financial support for authors ZH and AA was made available from the United States Bureau of Reclamation (USBR) Award No. R11AP81451 and the National Science Foundation (NSF) Award No. OISE-1243543. The contributions of author TJP were performed under the auspices of the Lawrence Livermore National Laboratory under contract DE-AC52-O7NA27344. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate-modeling groups for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and leads the development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. The authors also acknowledge the provision of surface air temperature and precipitation observational data by the Climatic Research Unit of the University of East Anglia via the British Atmospheric Data Centre(at http://badc.nerc.ac.uk) and by the University of Delaware via the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (at http://www.esrl.noaa.gov/ psd/).

References

Adler, R., Gu, G., Wang, J., Huffman, G., Curtis, S. & Bolvin, D. (2008), 'Relationships between global precipitation and surface temperature on interannual and longer timescales (1979–2006)', *Journal of Geophysical Research* **113**(D22), D22104.

AghaKouchak, A., Ciach, G. & Habib, E. (2010), 'Estimation of tail dependence coefficient in rainfall accumulation fields', *Advances in Water Resources* **33**(9), 1142–1149.

AghaKouchak, A., Easterling, D., Hsu, K., Schubert, S. & Sorooshian, S. (2012), *Extremes in a Changing Climate*, Springer, Springer Netherlands, Dordrecht.

Albright, T. P., Pidgeon, A. M., Rittenhouse, C. D., Clayton, M. K., Wardlow, B. D., Flather, C. H., Culbert, P. D. & Radeloff, V. C. (2010), 'Combined effects of heat waves and droughts on avian communities across the conterminous United States', *Ecosphere* **1**(5), art12.

Alexander, L., Zhang, X., Peterson, T., Caesar, J., Gleason, B., Klein Tank, A., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Ambenje, P., Rupa Kumar, K., Revadekar, J. & Griffiths, G. (2006), 'Global observed changes in daily climate extremes of temperature', *Journal of Geophysical Research* **111**, D05109.

Beniston, M. (2009), 'Trends in joint quantiles of temperature and precipitation in Europe since 1901 and projected for 2100', *Geophysical Research Letters* **36**, L07707.

Cooley, D., Nychka, D. & Naveau, P. (2007), 'Bayesian spatial modeling of extreme precipitation return levels', *Journal of the American Statistical Association* **102**(479), 824–840.

Easterling, D., Meehl, G., Parmesan, C., Changnon, S., Karl, T. & Mearns, L. (2000), 'Climate extremes: Observations, modeling, and impacts', *Science* **289**(5487), 2068–2074.

Estrella, N. & Menzel, A. (2012), 'Recent and future climate extremes arising from changes to the bivariate distribution of temperature and precipitation in Bavaria, Germany', *International Journal of Climatology* pp. n/a–n/a.

Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D., Ebi, K., Mastrandrea, M., Mach, K., Plattner, G., Allen, S. et al. (2012), *Managing the risks of extreme events and disasters to advance climate change adaptation*, Cambridge University Press Cambridge.

Hansen, J., Ruedy, R., Sato, M. & Lo, K. (2010), 'Global surface temperature change', *Reviews of Geophysics* **48**(4), RG4004.

Hegerl, G., Hanlon, H. & Beierkuhnlein, C. (2011), 'Climate science: elusive extremes', *Nature Geoscience* **4**(3), 142–143.

IPCC (2007), *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, Exit EPA Disclaimer Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Parry, Martin L., Canziani, Osvaldo F., Palutikof, Jean P., van der Linden, Paul J., and Hanson, Clair E. (eds.)]. Cambridge University Press, Cambridge, United Kingdom.

Jones, P., Lister, D., Osborn, T., Harpham, C., Salmon, M. & Morice, C. (2012), 'Hemispheric and large-scale land-surface air temperature variations: An extensive revision and an update to 2010', *Journal Of Geophysical Research-Atmospheres* **117**, D05127.

Katz, R. (2010), 'Statistics of extremes in climate change', *Climatic Change* **100**(1), 71–76.

Kenyon, J. & Hegerl, G. C. (2010), 'Influence of modes of climate variability on global precipitation extremes', *Journal of Climate* **23**(23), 6248–6262.

Lawrimore, J., Menne, M., Gleason, B., Williams, C., Wuertz, D., Vose, R. & Rennie, J. (2011), 'An overview of the Global Historical Climatology Network monthly mean temperature data set, version 3', *Journal of Geophysical Research* **116**(D19), D19121.

Legates, D. & Willmott, C. (1990*a*), 'Mean seasonal and spatial variability in gauge-corrected, global precipitation', *International Journal of Climatology* **10**(2), 111–127.

Legates, D. & Willmott, C. (1990*b*), 'Mean seasonal and spatial variability in global surface air temperature', *Theoretical and Applied Climatology* **41**(1-2), 11–21.

Liu, C., Allan, R. P. & Huffman, G. J. (2012), 'Co-variation of temperature and precipitation in CMIP5 models and satellite observations', *Geophysical Research Letters* **39**, L13803.

Lyon, B. (2009), 'Southern Africa summer drought and heat waves: observations and coupled model behavior', *Journal of Climate* **22**(22), 6033–6046.

Mitchell, T. & Jones, P. (2005), 'An improved method of constructing a database of monthly climate observations and associated high-resolution grids', *International Journal of Climatology* **25**(6), 693–712.

Morice, C. P., Kennedy, J. J., Rayner, N. A. & Jones, P. D. (2012), 'Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The hadcrut4 data set', *Journal of Geophysical Research: Atmospheres (1984–2012)*.

New, M., Hulme, M. & Jones, P. (1999), 'Representing twentieth-century space-time climate variability. part i: Development of a 1961-90 mean monthly terrestrial climatology', *Journal of Climate* **12**(3), 829–856.

New, M., Hulme, M. & Jones, P. (2000), 'Representing twentieth-century space-time climate variability. Part II: Development of 1901-96 monthly grids of terrestrial surface climate', *Journal of Climate* **13**(13), 2217–2238.

Nicholls, N., Gruza, G., Jouzel, J., Karl, T., Ogallo, L., Parker, D. et al. (1996), *Observed climate variability and change*, Cambridge University Press.

Nickl, E., Willmott, C. J., Matsuura, K. & Robeson, S. M. (2010), 'Changes in annual land-surface precipitation over the twentieth and early twenty-first century', *Annals of the Association of American Geographers* **100**(4), 729–739.

Peterson, T. C., Stott, P. A. & Herring, S. (2012), 'Explaining extreme events of 2011 from a climate perspective', *Bulletin of the American Meteorological Society* **93**(7), 1041–1067.

Rawlins, M., Bradley, R. & Diaz, H. (2012), 'Assessment of regional climate model simulation estimates over the northeast United States', *Journal of Geophysical Research: Atmospheres (1984–2012)*.

Sexton, D., Murphy, J., Collins, M. & Webb, M. (2012), 'Multivariate probabilistic projections using imperfect climate models part i: outline of methodology', *Climate dynamics* pp. 1–30.

Sheffield, J., Wood, E. & Roderick, M. (2012), 'Little change in global drought over the past 60 years', *Nature* **491**(7424), 435–438.

Sivakumar, M. (2006), 'Climate prediction and agriculture: current status and future challenges', *Climate Research* **33**(1), 3.

Smith, T. M., Arkin, P. A., Ren, L. & Shen, S. S. (2012), 'Improved reconstruction of global precipitation since 1900', *Journal of Atmospheric and Oceanic Technology* **29**(10), 1505–1517.

Tanarhte, M., Hadjinicolaou, P. & Lelieveld, J. (2012), 'Intercomparison of temperature and precipitation data sets based on observations in the Mediterranean and the Middle East', *Journal of Geophysical Research* **117**(D12), D12102.

Taylor, K. E., Stouffer, R. J. & Meehl, G. A. (2012), 'An Overview of CMIP5 and the Experiment Design', *Bulletin of the American Meteorological Society* **93**(4), 485–498.

Tebaldi, C. & Sansó, B. (2008), 'Joint projections of temperature and precipitation change from multiple climate models: a hierarchical Bayesian approach', *Journal of the Royal Statistical Society: Series A (Statistics in Society)* **172**(1), 83–106.

Thorne, P. W., Parker, D. E., Christy, J. R. & Mears, C. A. (2005), 'Uncertainties in climate trends: Lessons from upper-air temperature records', *Bulletin of the American Meteorological Society* **86**(10), 1437–1442.

Trenberth, K. & Shea, D. (2005), 'Relationships between precipitation and surface temperature', *Geophysical Research Letters* **32**(14), L14703.

Vose, R., Wuertz, D., Peterson, T. & Jones, P. (2005), 'An intercomparison of trends in surface air temperature analyses at the global, hemispheric, and grid-box scale', *Geophysical Research Letters* **32**(18), L18718.

Watterson, I. (2011), 'Calculation of joint PDFs for climate change with properties matching recent Australian projections', *Australian Meteorological and Oceanographic Journal* **61**(4), 12–31.

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Tank, A. K., Peterson, T. C., Trewin, B. & Zwiers,

F. W. (2011), 'Indices for monitoring changes in extremes based on daily temperature and precipitation data', *Wiley Interdisciplinary Reviews-Climate Change* **2**(6), 851–870.

Zhang, X., Vincent, L., Hogg, W. & Niitsoo, A. (2000), 'Temperature and precipitation trends in canada during the 20th century', *Atmosphere-Ocean* **38**(3), 395–429.

Zhao, W. & Khalil, M. (1993), 'The Relationship between Precipitation and Temperature over the Contiguous United States', *Journal of Climate* **6**, 1232–1240.

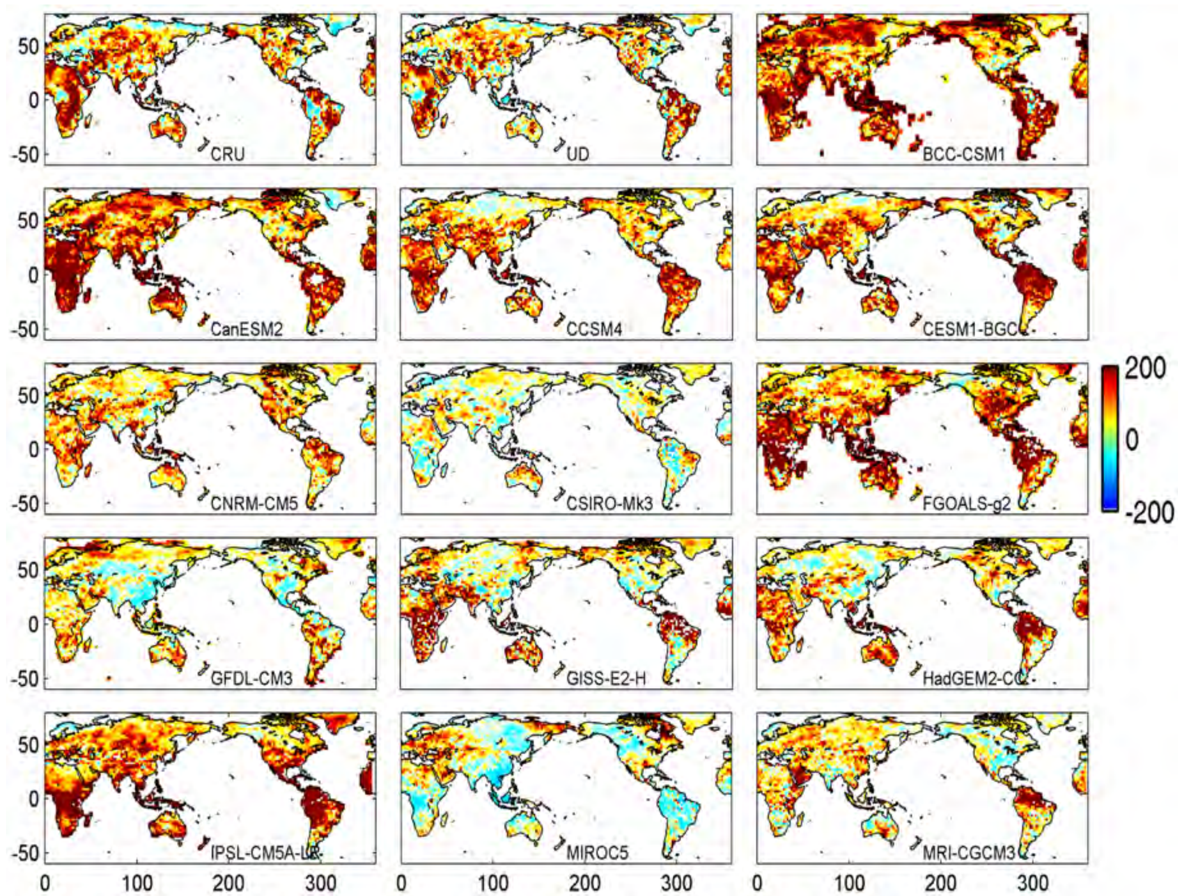

Figure 1: Percentage change in the occurrences of the Warm/Wet extremes for the period 1978-2004 vs. 1951-1977 in the CRU and UD observations (top left panels) and in each selected CMIP5 model simulation.

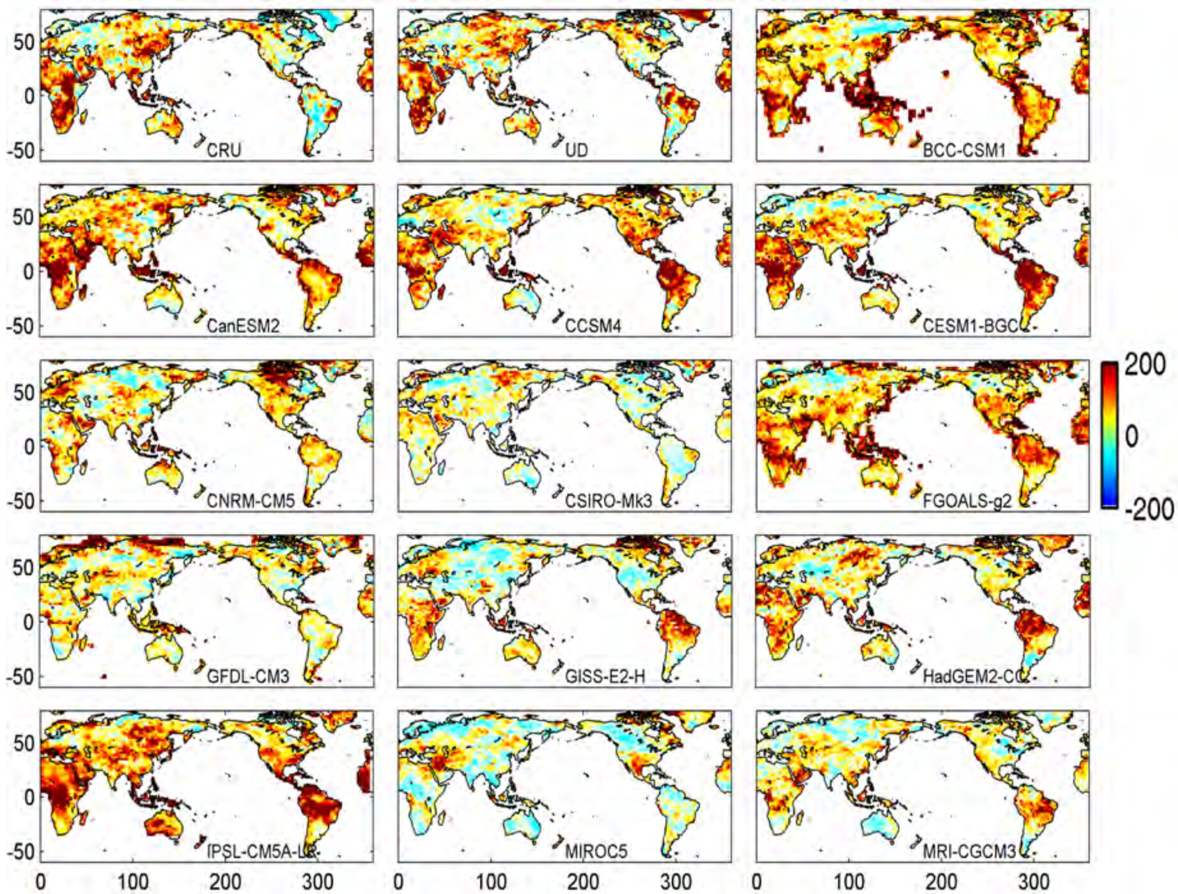

Figure 2: Percentage change in the occurrences of the Warm/Dry extremes for the period 1978-2004 vs. 1951-1977 in the CRU and UD observations (top left panels) and in each selected CMIP5 model simulation.

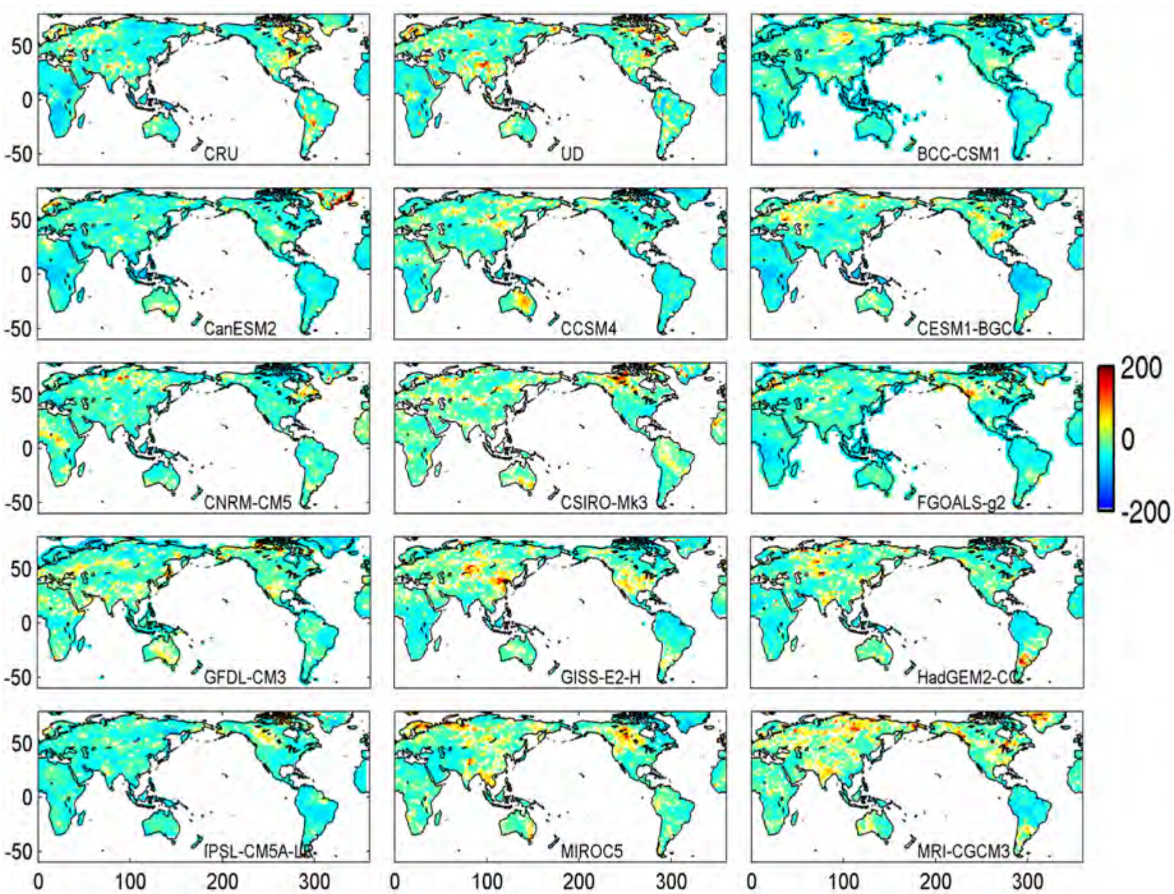

Figure 3: Percentage change in the occurrences of the Cold/Wet extremes for the period 1978-2004 vs. 1951-1977 in the CRU and UD observations (top left panels) and in each selected CMIP5 model simulation.

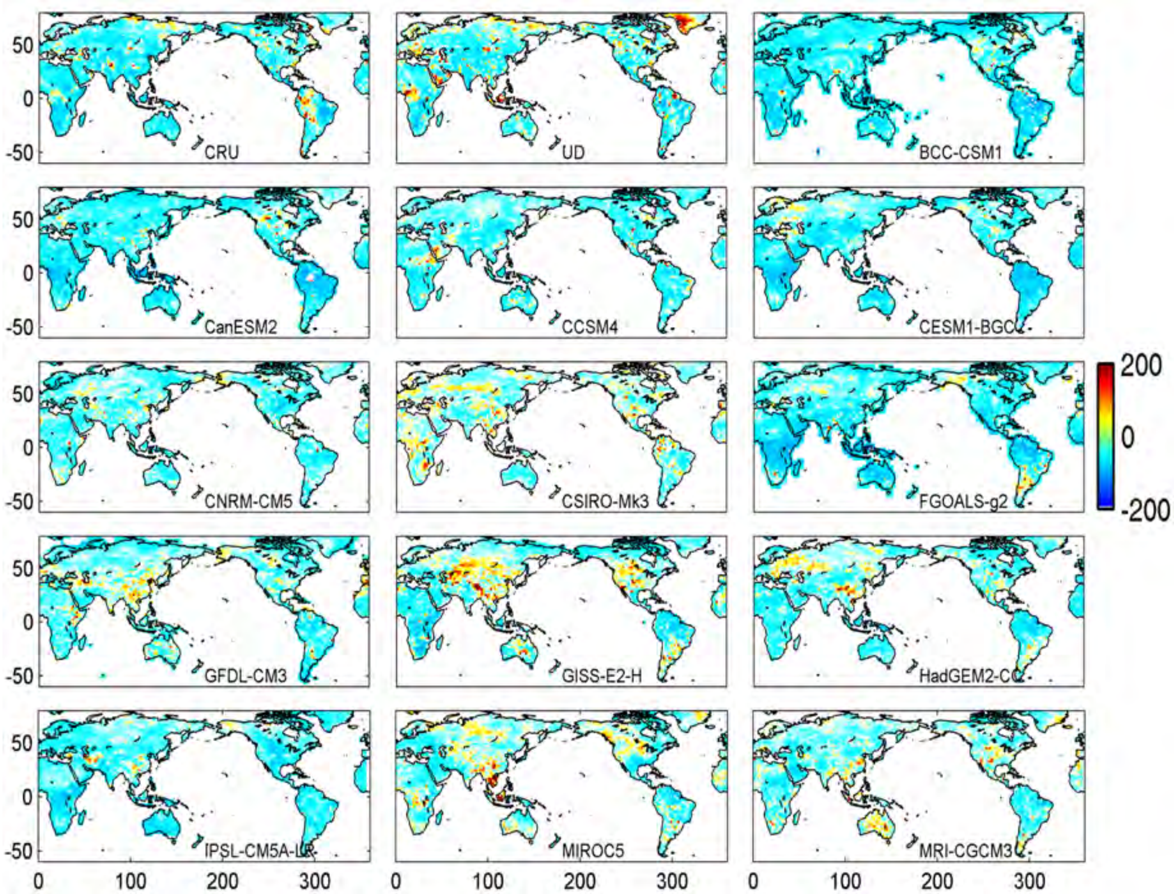

Figure 4: Percentage change in the occurrences of the Cold/Dry extremes for the period 1978-2004 vs. 1951-1977 in the CRU and UD observations (top left panels) and in each selected CMIP5 model simulation.

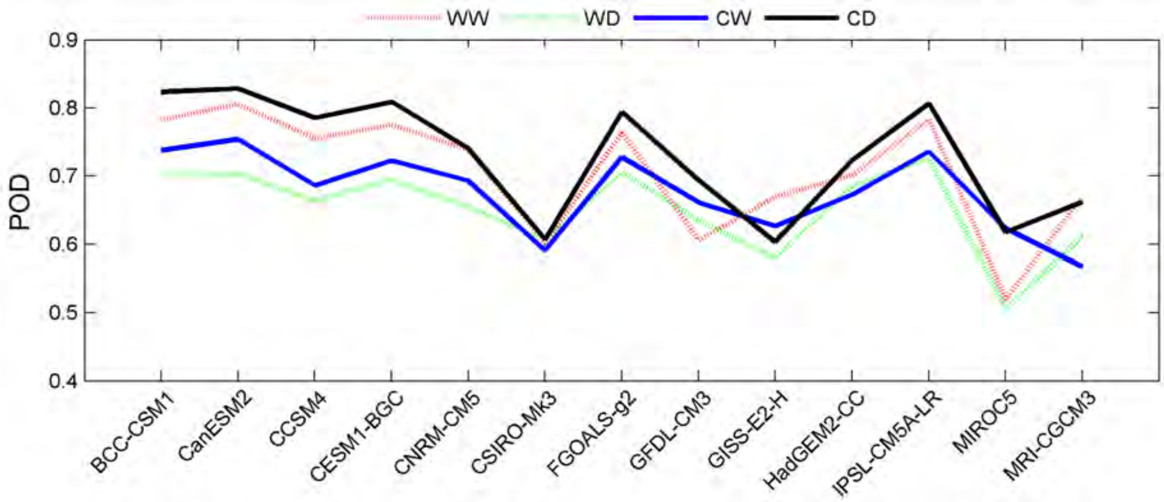

Figure 5: The probability of detection (POD) of the sign of change in the CMIP5 climate-model simulations from the period 1951-77 to the period 1978-2004 for the four combinations of Warm/Wet, Warm/Dry, Cold/Wet, and Cold/Dry extremes with respect to CRU observations. The POD is defined as the fraction of grids in which the sign of change in the number of joint occurrences (increase, decrease, neutral) in CMIP5 model simulations agrees with the ground-based observations.

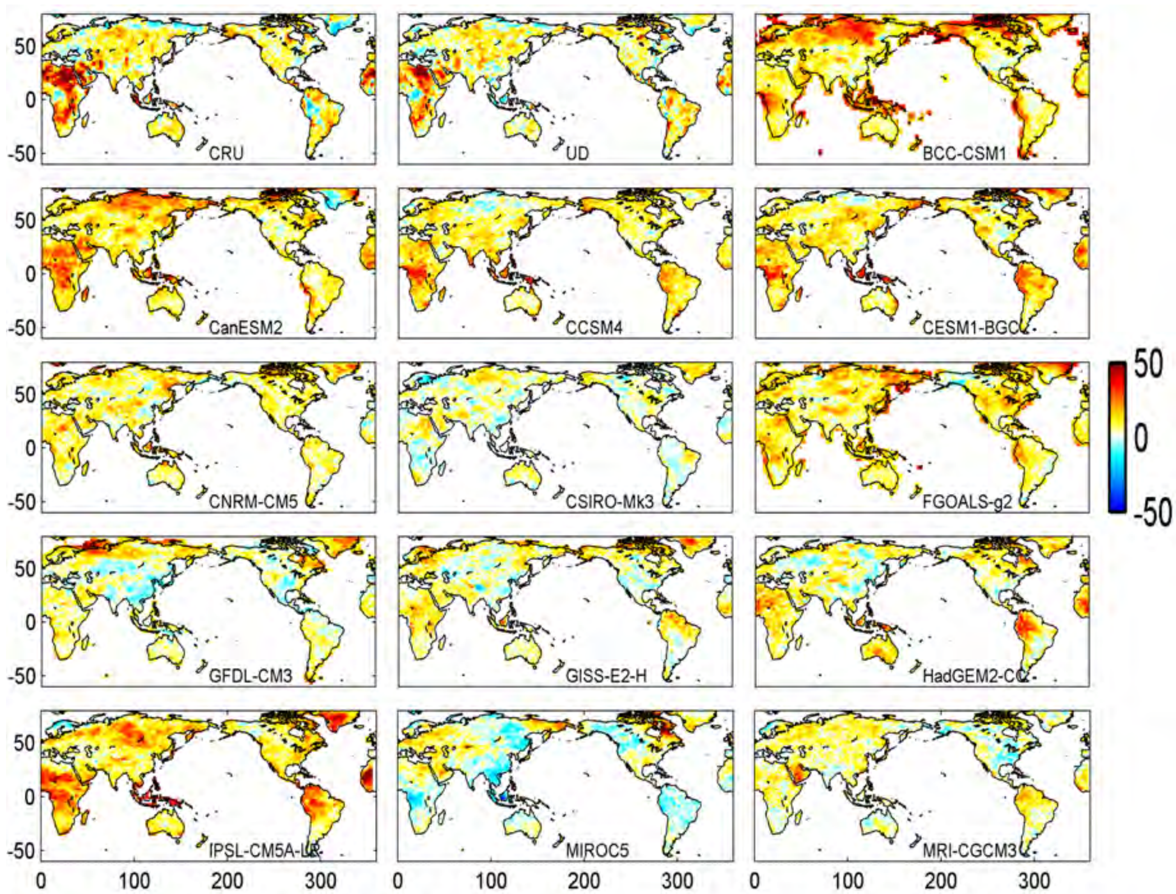

Figure S1. Changes in the absolute number of concurrent Warm/Wet extremes in the period 1978-2004 vs. 1951-1977 in the CRU and UD observations (top left panels) and in each selected CMIP5 model simulation.

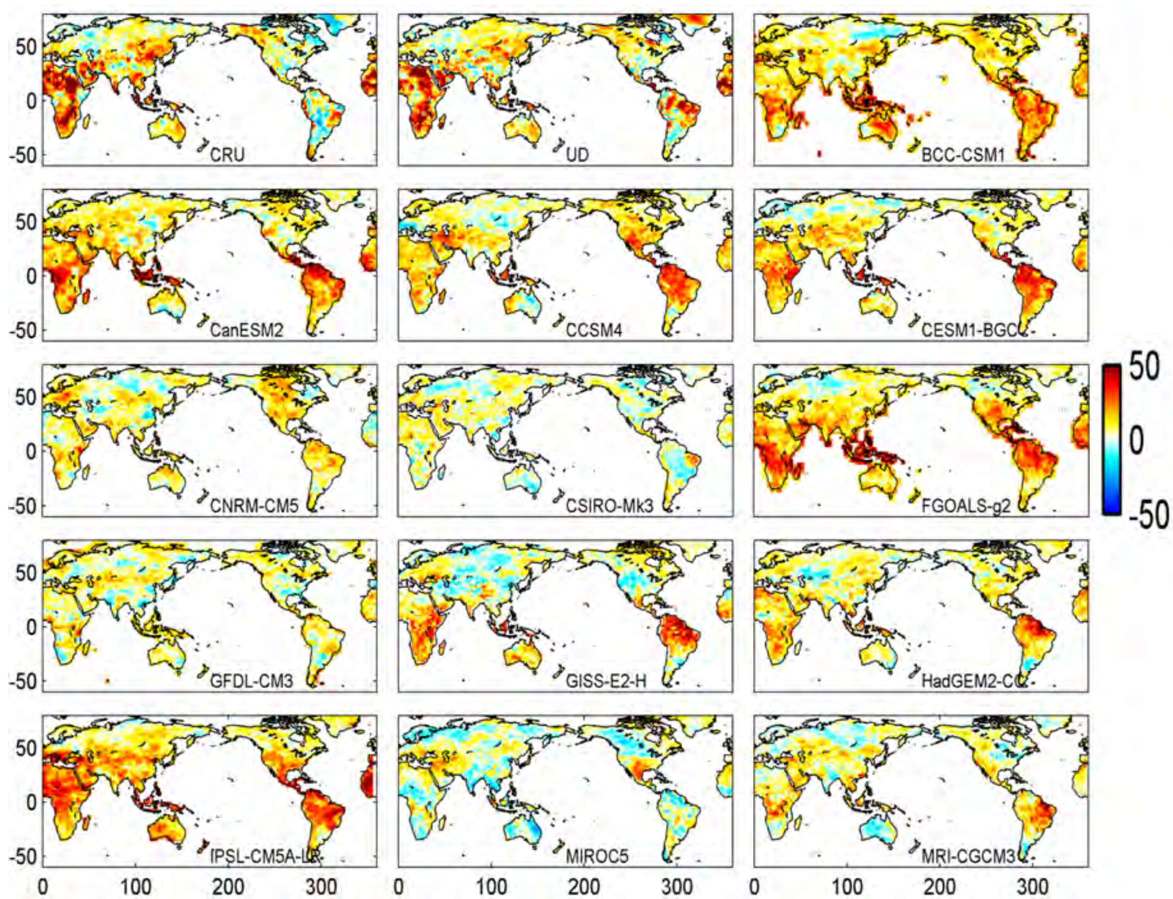

Figure S2. Changes in the absolute number of concurrent Warm/Dry extremes in the period 1978-2004 vs. 1951-1977 in the CRU and UD observations (top left panels) and in each selected CMIP5 model simulation.

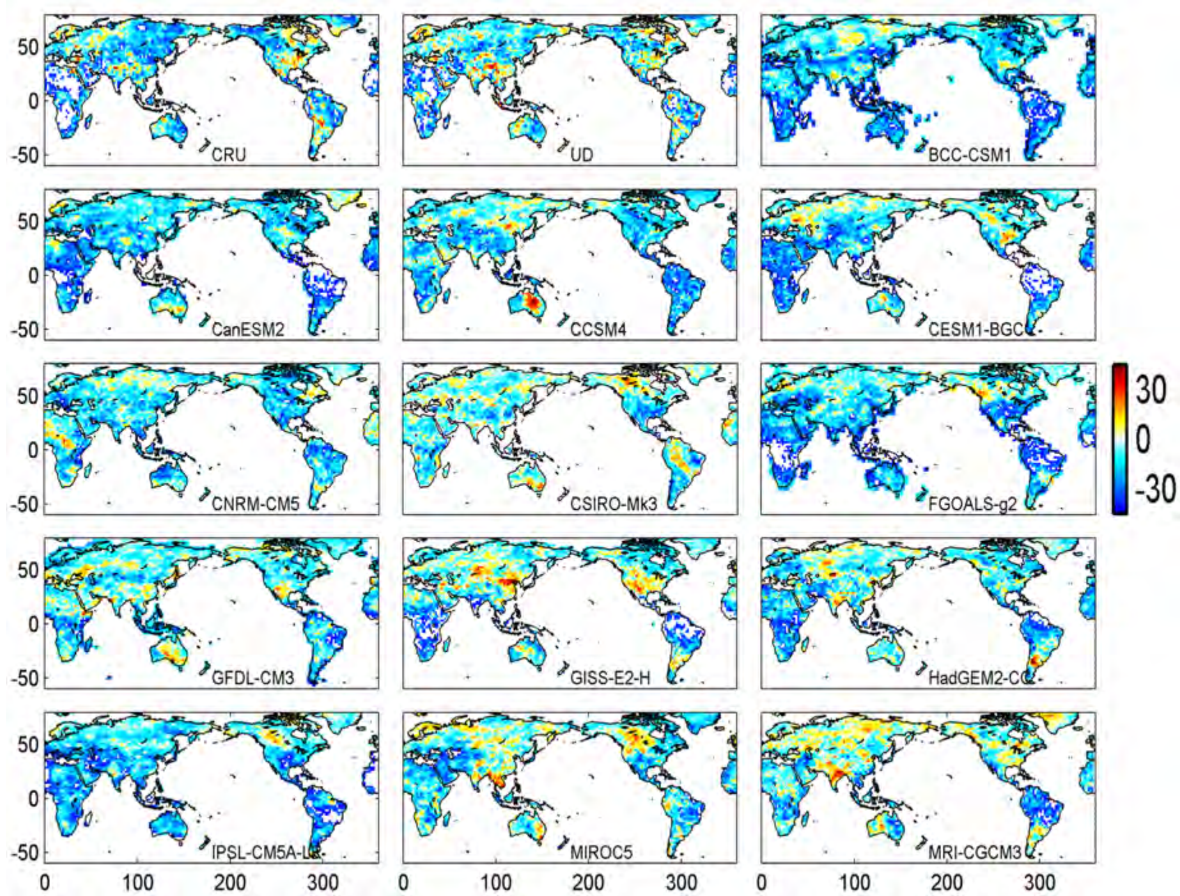

Figure S3. Changes in the absolute number of concurrent Cold/Wet extremes in the period 1978-2004 vs. 1951-1977 in the CRU and UD observations (top left panels) and in each selected CMIP5 model simulation.

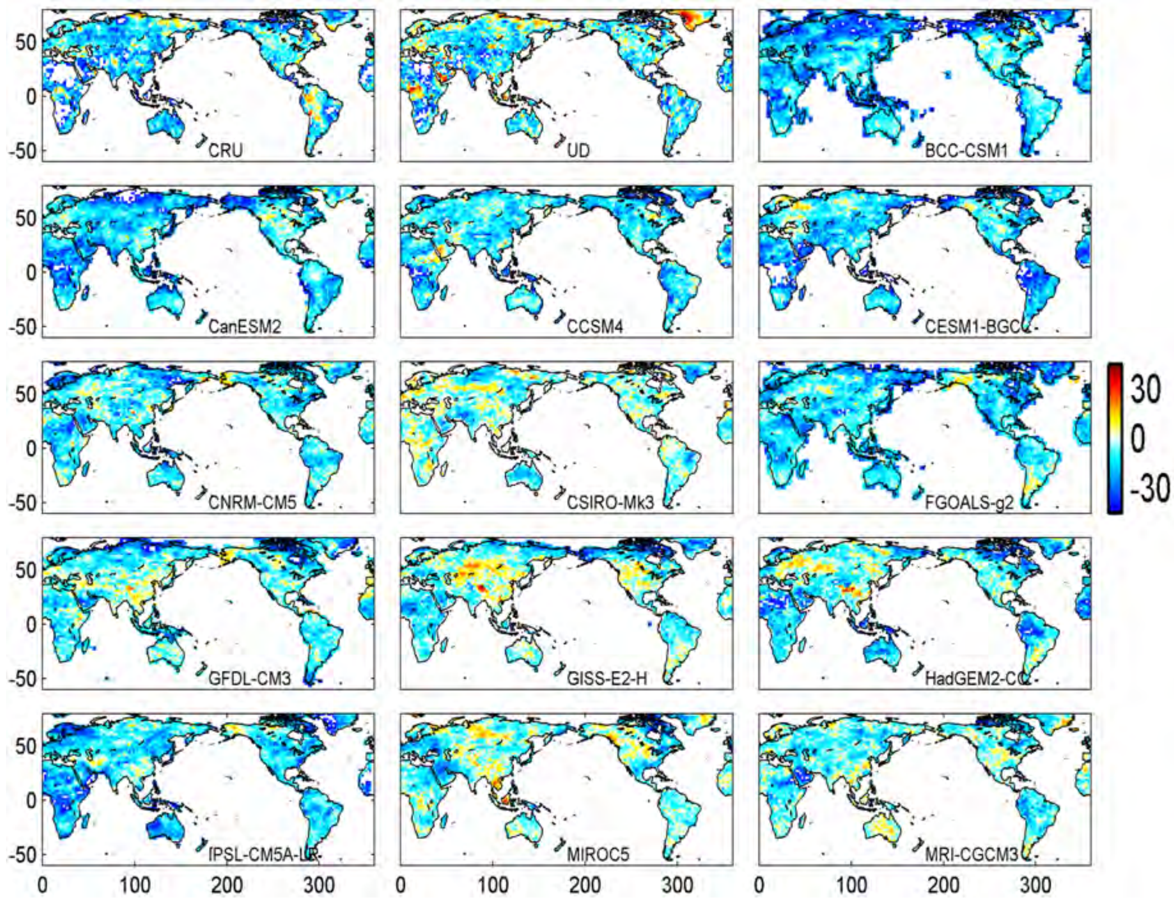

Figure S4. Changes in the absolute number of concurrent Cold/Dry extremes in the period 1978-2004 vs. 1951-1977 in the CRU and UD observations (top left panels) and in each selected CMIP5 model simulation.